

# First observation of the P-wave spin-singlet bottomonium states $h_b(1P)$ and $h_b(2P)$

I. Adachi,<sup>8</sup> H. Aihara,<sup>50</sup> K. Arinstein,<sup>1</sup> D. M. Asner,<sup>39</sup> T. Aushev,<sup>16</sup> T. Aziz,<sup>46</sup> A. M. Bakich,<sup>45</sup> E. Barberio,<sup>28</sup> V. Bhardwaj,<sup>40</sup> B. Bhuyan,<sup>10</sup> A. Bondar,<sup>1</sup> M. Bračko,<sup>26,17</sup> T. E. Browder,<sup>7</sup> P. Chang,<sup>33</sup> A. Chen,<sup>31</sup> P. Chen,<sup>33</sup> B. G. Cheon,<sup>6</sup> K. Chilikin,<sup>16</sup> I.-S. Cho,<sup>55</sup> K. Cho,<sup>20</sup> Y. Choi,<sup>44</sup> J. Dalseno,<sup>27,47</sup> M. Danilov,<sup>16</sup> Z. Drásal,<sup>2</sup> S. Eidelman,<sup>1</sup> D. Epifanov,<sup>1</sup> S. Esen,<sup>3</sup> J. E. Fast,<sup>39</sup> M. Feindt,<sup>19</sup> V. Gaur,<sup>46</sup> N. Gabyshev,<sup>1</sup> A. Garmash,<sup>1</sup> Y. M. Goh,<sup>6</sup> T. Hara,<sup>8</sup> K. Hayasaka,<sup>29</sup> H. Hayashii,<sup>30</sup> Y. Hoshi,<sup>48</sup> W.-S. Hou,<sup>33</sup> Y. B. Hsiung,<sup>33</sup> H. J. Hyun,<sup>22</sup> T. Iijima,<sup>29</sup> A. Ishikawa,<sup>49</sup> M. Iwabuchi,<sup>55</sup> Y. Iwasaki,<sup>8</sup> T. Julius,<sup>28</sup> J. H. Kang,<sup>55</sup> N. Katayama,<sup>8</sup> T. Kawasaki,<sup>36</sup> H. Kichimi,<sup>8</sup> H. O. Kim,<sup>22</sup> J. B. Kim,<sup>21</sup> K. T. Kim,<sup>21</sup> M. J. Kim,<sup>22</sup> Y. J. Kim,<sup>20</sup> K. Kinoshita,<sup>3</sup> B. R. Ko,<sup>21</sup> N. Kobayashi,<sup>41,51</sup> S. Koblitz,<sup>27</sup> P. Križan,<sup>24,17</sup> T. Kuhr,<sup>19</sup> T. Kumita,<sup>52</sup> A. Kuzmin,<sup>1</sup> Y.-J. Kwon,<sup>55</sup> J. S. Lange,<sup>4</sup> S.-H. Lee,<sup>21</sup> J. Li,<sup>43</sup> J. Libby,<sup>11</sup> C. Liu,<sup>42</sup> D. Liventsev,<sup>16</sup> R. Louvot,<sup>23</sup> J. MacNaughton,<sup>8</sup> D. Matvienko,<sup>1</sup> S. McOnie,<sup>45</sup> K. Miyabayashi,<sup>30</sup> H. Miyata,<sup>36</sup> Y. Miyazaki,<sup>29</sup> R. Mizuk,<sup>16</sup> G. B. Mohanty,<sup>46</sup> R. Mussa,<sup>15</sup> Y. Nagasaka,<sup>9</sup> E. Nakano,<sup>38</sup> M. Nakao,<sup>8</sup> H. Nakazawa,<sup>31</sup> Z. Natkaniec,<sup>34</sup> S. Neubauer,<sup>19</sup> S. Nishida,<sup>8</sup> K. Nishimura,<sup>7</sup> O. Nitoh,<sup>53</sup> T. Nozaki,<sup>8</sup> T. Ohshima,<sup>29</sup> S. Okuno,<sup>18</sup> S. L. Olsen,<sup>43,7</sup> Y. Onuki,<sup>49</sup> P. Pakhlov,<sup>16</sup> G. Pakhlova,<sup>16</sup> H. Park,<sup>22</sup> T. K. Pedlar,<sup>25</sup> R. Pestotnik,<sup>17</sup> M. Petrič,<sup>17</sup> L. E. Piilonen,<sup>54</sup> A. Poluektov,<sup>1</sup> M. Ritter,<sup>27</sup> M. Röhrken,<sup>19</sup> S. Ryu,<sup>43</sup> H. Sahoo,<sup>7</sup> Y. Sakai,<sup>8</sup> T. Sanuki,<sup>49</sup> O. Schneider,<sup>23</sup> C. Schwanda,<sup>13</sup> A. J. Schwartz,<sup>3</sup> K. Senyo,<sup>29</sup> O. Seon,<sup>29</sup> M. E. Sevir,<sup>28</sup> V. Shebalin,<sup>1</sup> T.-A. Shibata,<sup>41,51</sup> J.-G. Shiu,<sup>33</sup> B. Shwartz,<sup>1</sup> F. Simon,<sup>27,47</sup> P. Smerkol,<sup>17</sup> Y.-S. Sohn,<sup>55</sup> A. Sokolov,<sup>14</sup> E. Solovieva,<sup>16</sup> S. Stanič,<sup>37</sup> M. Starič,<sup>17</sup> M. Sumihama,<sup>41,5</sup> G. Tatishvili,<sup>39</sup> Y. Teramoto,<sup>38</sup> K. Trabelsi,<sup>8</sup> M. Uchida,<sup>41,51</sup> S. Uehara,<sup>8</sup> Y. Unno,<sup>6</sup> S. Uno,<sup>8</sup> S. E. Vahsen,<sup>7</sup> G. Varner,<sup>7</sup> K. E. Varvell,<sup>45</sup> A. Vinokurova,<sup>1</sup> C. H. Wang,<sup>32</sup> X. L. Wang,<sup>12</sup> Y. Watanabe,<sup>18</sup> J. Wicht,<sup>8</sup> E. Won,<sup>21</sup> B. D. Yabsley,<sup>45</sup> Y. Yamashita,<sup>35</sup> V. Zhilich,<sup>1</sup> and A. Zupanc<sup>19</sup>

(The Belle Collaboration)

<sup>1</sup>*Budker Institute of Nuclear Physics SB RAS and Novosibirsk State University, Novosibirsk 630090*

<sup>2</sup>*Faculty of Mathematics and Physics, Charles University, Prague*

<sup>3</sup>*University of Cincinnati, Cincinnati, Ohio 45221*

<sup>4</sup>*Justus-Liebig-Universität Gießen, Gießen*

<sup>5</sup>*Gifu University, Gifu*

<sup>6</sup>*Hanyang University, Seoul*

<sup>7</sup>*University of Hawaii, Honolulu, Hawaii 96822*

<sup>8</sup>*High Energy Accelerator Research Organization (KEK), Tsukuba*

<sup>9</sup>*Hiroshima Institute of Technology, Hiroshima*

<sup>10</sup>*Indian Institute of Technology Guwahati, Guwahati*

<sup>11</sup>*Indian Institute of Technology Madras, Madras*

<sup>12</sup>*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing*

<sup>13</sup>*Institute of High Energy Physics, Vienna*

<sup>14</sup>*Institute of High Energy Physics, Protvino*

<sup>15</sup>*INFN - Sezione di Torino, Torino*

<sup>16</sup>*Institute for Theoretical and Experimental Physics, Moscow*

<sup>17</sup>*J. Stefan Institute, Ljubljana*

<sup>18</sup>*Kanagawa University, Yokohama*

<sup>19</sup>*Institut für Experimentelle Kernphysik, Karlsruher Institut für Technologie, Karlsruhe*

<sup>20</sup>*Korea Institute of Science and Technology Information, Daejeon*

<sup>21</sup>*Korea University, Seoul*

<sup>22</sup>*Kyungpook National University, Taegu*

<sup>23</sup>*École Polytechnique Fédérale de Lausanne (EPFL), Lausanne*

<sup>24</sup>*Faculty of Mathematics and Physics, University of Ljubljana, Ljubljana*

<sup>25</sup>*Luther College, Decorah, Iowa 52101*

<sup>26</sup>*University of Maribor, Maribor*

<sup>27</sup>*Max-Planck-Institut für Physik, München*

<sup>28</sup>*University of Melbourne, School of Physics, Victoria 3010*

<sup>29</sup>*Nagoya University, Nagoya*

<sup>30</sup>*Nara Women's University, Nara*

<sup>31</sup>*National Central University, Chung-li*

<sup>32</sup>*National United University, Miao Li*

<sup>33</sup>*Department of Physics, National Taiwan University, Taipei*

<sup>34</sup>*H. Niewodniczanski Institute of Nuclear Physics, Krakow*

<sup>35</sup>*Nippon Dental University, Niigata*

<sup>36</sup>*Niigata University, Niigata*

<sup>37</sup>University of Nova Gorica, Nova Gorica

<sup>38</sup>Osaka City University, Osaka

<sup>39</sup>Pacific Northwest National Laboratory, Richland, Washington 99352

<sup>40</sup>Panjab University, Chandigarh

<sup>41</sup>Research Center for Nuclear Physics, Osaka

<sup>42</sup>University of Science and Technology of China, Hefei

<sup>43</sup>Seoul National University, Seoul

<sup>44</sup>Sungkyunkwan University, Suwon

<sup>45</sup>School of Physics, University of Sydney, NSW 2006

<sup>46</sup>Tata Institute of Fundamental Research, Mumbai

<sup>47</sup>Excellence Cluster Universe, Technische Universität München, Garching

<sup>48</sup>Tohoku Gakuin University, Tagajo

<sup>49</sup>Tohoku University, Sendai

<sup>50</sup>Department of Physics, University of Tokyo, Tokyo

<sup>51</sup>Tokyo Institute of Technology, Tokyo

<sup>52</sup>Tokyo Metropolitan University, Tokyo

<sup>53</sup>Tokyo University of Agriculture and Technology, Tokyo

<sup>54</sup>CNP, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061

<sup>55</sup>Yonsei University, Seoul

(Dated: August 2, 2011)

We report the first observation of the spin-singlet bottomonium states  $h_b(1P)$  and  $h_b(2P)$  produced in the reaction  $e^+e^- \rightarrow h_b(nP)\pi^+\pi^-$  using a  $121.4 \text{ fb}^{-1}$  data sample collected at energies near the  $\Upsilon(5S)$  resonance with the Belle detector at the KEKB asymmetric-energy  $e^+e^-$  collider. We determine  $M[h_b(1P)] = (9898.3 \pm 1.1^{+1.0}_{-1.1}) \text{ MeV}/c^2$  and  $M[h_b(2P)] = (10259.8 \pm 0.6^{+1.4}_{-1.0}) \text{ MeV}/c^2$ , which correspond to  $P$ -wave hyperfine splittings  $\Delta M_{\text{HF}} = (+1.6 \pm 1.5) \text{ MeV}/c^2$  and  $(+0.5^{+1.6}_{-1.2}) \text{ MeV}/c^2$ , respectively. The  $h_b(1P)$  and  $h_b(2P)$  are observed with significances of  $5.5\sigma$  and  $11.2\sigma$ , respectively. We also report measurements of the cross sections for  $e^+e^- \rightarrow h_b(nP)\pi^+\pi^-$  relative to that for  $e^+e^- \rightarrow \Upsilon(2S)\pi^+\pi^-$ .

PACS numbers: 14.40.Pq, 13.25.Gv, 12.39.Pn

Bottomonium is the bound system of  $b\bar{b}$  quarks and is considered an excellent laboratory to study Quantum Chromodynamics (QCD) at low energies. The system is approximately non-relativistic due to the large  $b$  quark mass, and therefore the quark-antiquark QCD potential can be investigated via  $b\bar{b}$  spectroscopy [1].

The spin-singlet states  $h_b(nP)$  and  $\eta_b(nS)$  alone provide information concerning the spin-spin (or hyperfine) interaction in bottomonium. Measurements of the  $h_b(nP)$  masses provide unique access to the  $P$ -wave hyperfine splitting,  $\Delta M_{\text{HF}} \equiv \langle M(n^3P_J) \rangle - M(n^1P_1)$ , the difference between the spin-weighted average mass of the  $P$ -wave triplet states ( $\chi_{bJ}(nP)$  or  $n^3P_J$ ) and that of the corresponding  $h_b(nP)$ , or  $n^1P_1$ . These splittings are predicted to be close to zero [2], and recent measurements of the  $h_c(1P)$  mass correspond to a  $P$ -wave hyperfine splitting that validates this expectation for the  $1P$  level in charmonium:  $\Delta M_{\text{HF}} = (0.00 \pm 0.15) \text{ MeV}/c^2$  [3].

Recently, the CLEO Collaboration observed the process  $e^+e^- \rightarrow h_c(1P)\pi^+\pi^-$  at a rate comparable to that for  $e^+e^- \rightarrow J/\psi\pi^+\pi^-$  in data taken above open charm threshold [4]. Such a large rate was unexpected because the production of  $h_c(1P)$  requires a  $c$ -quark spin-flip, while production of  $J/\psi$  does not. Similarly, the Belle Collaboration observed anomalously high rates for  $e^+e^- \rightarrow \Upsilon(nS)\pi^+\pi^-$  ( $n = 1, 2, 3$ ) at energies near the  $\Upsilon(5S)$  mass [5]. Together, these observations motivate

a search for  $e^+e^- \rightarrow \pi^+\pi^-h_b(nP)$  above open-bottom threshold at the  $\Upsilon(5S)$  resonance.

In this Letter, we report the first observation of the  $h_b(1P)$  and  $h_b(2P)$  produced via  $e^+e^- \rightarrow h_b(nP)\pi^+\pi^-$  in the  $\Upsilon(5S)$  region. We use a  $121.4 \text{ fb}^{-1}$  data sample collected near the peak of the  $\Upsilon(5S)$  resonance ( $\sqrt{s} \sim 10.865 \text{ GeV}$ ) with the Belle detector [6] at the KEKB asymmetric-energy  $e^+e^-$  collider [7].

We observe the  $h_b(nP)$  states in the  $\pi^+\pi^-$  missing mass spectrum of hadronic events. The  $\pi^+\pi^-$  missing mass is defined as  $M_{\text{miss}}^2 \equiv (P_{\Upsilon(5S)} - P_{\pi^+\pi^-})^2$ , where  $P_{\Upsilon(5S)}$  is the 4-momentum of the  $\Upsilon(5S)$  determined from the beam momenta and  $P_{\pi^+\pi^-}$  is the 4-momentum of the  $\pi^+\pi^-$  system. The  $\pi^+\pi^-$  transitions between  $\Upsilon(nS)$  states provide high-statistics reference signals.

Our hadronic event selection requires a reconstructed primary vertex consistent with the run-averaged interaction point (IP), at least three high-quality charged tracks, a total visible energy greater than  $0.2\sqrt{s}$ , a total neutral energy of  $(0.1 - 0.8)\sqrt{s}$ , more than one large-angle cluster in the electromagnetic calorimeter and that the total center-of-mass momentum have longitudinal component smaller than  $0.5\sqrt{s}$  [8]. The  $\pi^+\pi^-$  candidates are pairs of well reconstructed, oppositely charged tracks that are identified as pions and do not satisfy electron-identification criteria. Continuum  $e^+e^- \rightarrow q\bar{q}$  ( $q = u, d, s, c$ ) background is suppressed by requir-

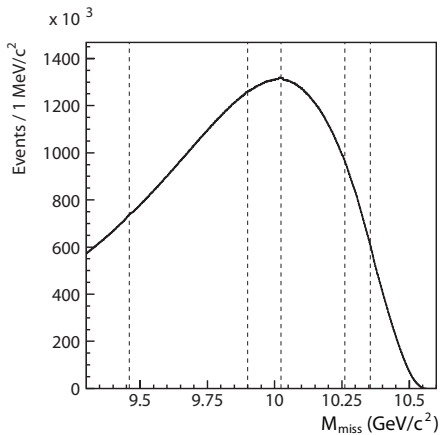


FIG. 1. The  $M_{\text{miss}}$  distribution for the selected  $\pi^+\pi^-$  pairs. Vertical lines indicate the locations of the  $\Upsilon(1S)$ ,  $h_b(1P)$ ,  $\Upsilon(2S)$ ,  $h_b(2P)$  and  $\Upsilon(3S)$  signals.

ing the ratio of the second to zeroth Fox-Wolfram moments to satisfy  $R_2 < 0.3$  [9]. The resulting  $M_{\text{miss}}$  spectrum, which is dominated by combinatoric  $\pi^+\pi^-$  pairs, is shown in Fig. 1.

Prior to fitting the inclusive  $M_{\text{miss}}$  spectrum we study reference channels and peaking backgrounds arising from  $\pi^+\pi^-$  transitions between  $\Upsilon(nS)$  states. A high purity sample of such transitions is obtained by reconstructing  $\mu^+\mu^-$  pairs in the event in addition to the  $\pi^+\pi^-$  pair. For these studies the hadronic event selection criteria are not applied, while for the  $\mu^+\mu^-$  pair we use the same selection as was employed in Ref. [5]. MC studies indicate that the shape of the peaks in  $M_{\text{miss}}$  is independent of whether the  $\pi^+\pi^-$  are reconstructed in the hadronic environment or in this much cleaner environment. In addition, to suppress radiative Bhabha events in which the photon converts, producing a fake  $\pi^+\pi^-$ , we require that the opening angle between the candidate pions in the laboratory frame satisfies  $\cos\theta_{\pi^+\pi^-} < 0.95$ . In Fig. 2 (a) we present the two-dimensional distribution of  $\mu^+\mu^-$  mass  $M_{\mu^+\mu^-}$  vs.  $M_{\text{miss}}$  for events satisfying these criteria.

Clear peaks are visible along a diagonal band, where  $M_{\mu^+\mu^-}$  is roughly equal to  $M_{\text{miss}}$ , and correspond to fully reconstructed  $\Upsilon(5S) \rightarrow \Upsilon(nS)\pi^+\pi^- \rightarrow \mu^+\mu^-\pi^+\pi^-$  events. Also along the diagonal is a diffuse background of events that arise due to the process  $e^+e^- \rightarrow \mu^+\mu^-\gamma(\rightarrow e^+e^-)$ , where the conversion pair is reconstructed as  $\pi^+\pi^-$ , or from non-resonant  $e^+e^- \rightarrow \mu^+\mu^-\pi^+\pi^-$  events. Events from the band satisfying  $|M_{\text{miss}} - M_{\mu^+\mu^-}| < 150 \text{ MeV}/c^2$  are projected onto the  $M_{\text{miss}}$  axis and fitted to the sum of a linear background and a Gaussian joined to a power-law tail on the high mass side. The high-side tail is due to Initial State Radiation (ISR) photons. This latter function is analogous to the well-known Crystal Ball function [10] but has the tail on the higher rather than lower side. We thus refer to it as a 'reversed Crystal Ball' (rCB) function. The fitted  $M_{\text{miss}}$  spectra

TABLE I. The yield, mass and width for signals reconstructed using  $M_{\text{miss}}$  from the exclusive  $\mu^+\mu^-\pi^+\pi^-$  selection. Each mass is consistent with the world average [11].

	Yield	Mass, $\text{MeV}/c^2$	$\sigma$ , $\text{MeV}/c^2$
$\Upsilon(1S)$	$1894 \pm 61$	$9459.96 \pm 0.23$	$7.68 \pm 0.21$
$\Upsilon(2S)$	$2322 \pm 60$	$10023.34 \pm 0.22$	$6.60 \pm 0.20$
$\Upsilon(3S)$	$661^{+39}_{-30}$	$10355.66^{+0.56}_{-0.39}$	$5.98^{+0.62}_{-0.37}$

from this band are shown in Figs. 2 (b)-(d), and the resulting yields, masses and width of the rCB function for the  $\Upsilon(nS)$  states are displayed in Table I. The masses obtained are consistent with the world average values [11].

The structures in the horizontal band in Fig. 2 (a), where  $M_{\mu^+\mu^-}$  is roughly equal to  $M[\Upsilon(1S)]$ , arise from events in which a daughter  $\Upsilon(1S)$  in the event decays to  $\mu^+\mu^-$ . In Figs. 2 (e)-(f) we present  $M_{\text{miss}}$  projections from this band, subject to the requirement  $|M_{\mu^+\mu^-} - M[\Upsilon(1S)]| < 150 \text{ MeV}/c^2$ . The peaks at the  $\Upsilon(3S)$  and  $\Upsilon(2S)$  masses arise from events having  $\pi^+\pi^-$  transitions to  $\Upsilon(3S)$  or  $\Upsilon(2S)$ , followed by inclusive production of  $\Upsilon(1S)$ , and are fitted to rCB functions. Peaks at  $9.97 \text{ GeV}/c^2$  and  $10.30 \text{ GeV}/c^2$  arise from events in which a  $\Upsilon(3S)$  or  $\Upsilon(2S)$  is produced inclusively in  $\Upsilon(5S)$  decays or via ISR, and then decays to  $\Upsilon(1S)\pi^+\pi^-$ , and are fitted to single and double Gaussians, respectively.

The threshold for inclusive  $K_S^0$  production results in a sharp rise in the  $M_{\text{miss}}$  spectrum, due to  $K_S^0 \rightarrow \pi^+\pi^-$ , very close to the mass of  $\Upsilon(3S)$ . Rather than veto  $\pi^+\pi^-$  combinations with invariant masses near  $M(K_S^0)$ , which significantly distorts the  $M_{\text{miss}}$  spectrum in the vicinity, we obtain the  $K_S^0$  contamination by fitting the  $\pi^+\pi^-$  invariant mass corresponding to bins of  $M_{\text{miss}}$ .

The  $M_{\text{miss}}$  spectrum is divided into three adjacent regions with boundaries at  $M_{\text{miss}} = 9.3, 9.8, 10.1$  and  $10.45 \text{ GeV}/c^2$  and fitted separately in each region. In the first two regions, we use a 6th-order Chebyshev polynomial, while in the third we use a 7th-order one. In the third region, prior to fitting, we subtract the contribution due to  $K_S^0 \rightarrow \pi^+\pi^-$  bin-by-bin. The signal component of the fit includes all signals seen in the  $\mu^+\mu^-\pi^+\pi^-$  data as well as those arising from  $\pi^+\pi^-$  transitions to  $h_b(nP)$  and  $\Upsilon(1D)$ . We fit these additional signals using the tail parameters of the  $\Upsilon(2S)$  and fixed widths found by linear interpolation in mass from the widths of the exclusively-reconstructed  $\Upsilon(nS)$  peaks. The peak positions of all signals are floated, except that for  $\Upsilon(3S) \rightarrow \Upsilon(1S)\pi^+\pi^-$ , which is poorly constrained by the fit. The confidence levels of the fits in the three regions are 3.0%, 0.5% and 0.4%, respectively. The  $M_{\text{miss}}$  spectrum, after subtraction of both the combinatoric and  $K_S^0 \rightarrow \pi^+\pi^-$  contributions is shown with the fitted signal functions overlaid in Fig. 3. The signal parameters are listed in Table II.

We studied several sources of systematic uncertainty.

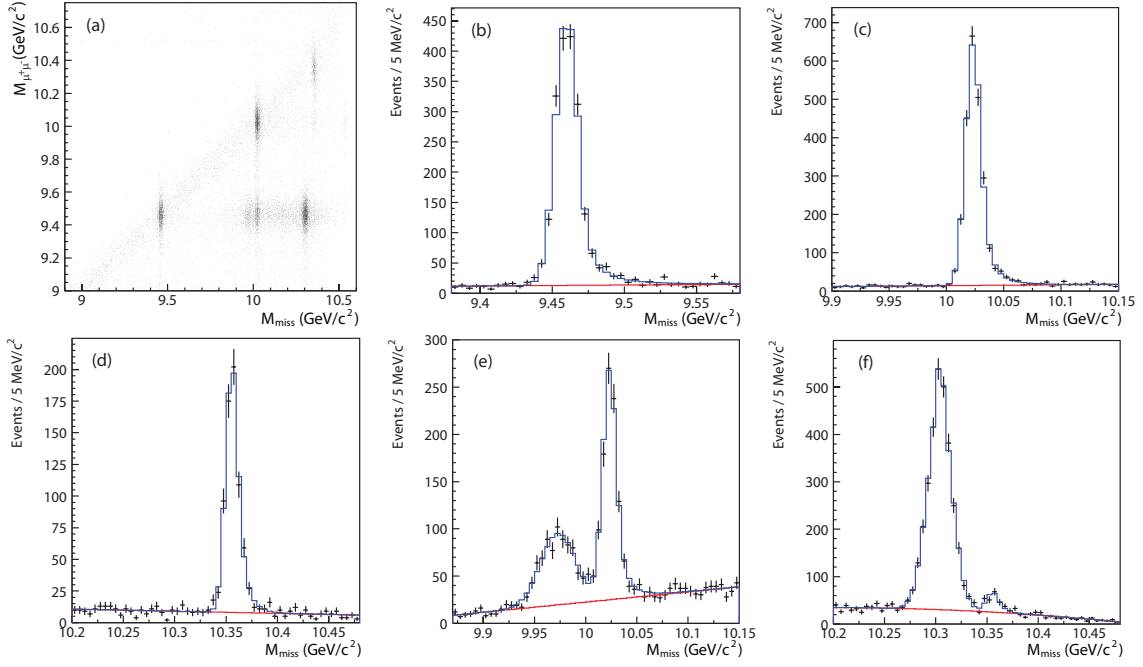


FIG. 2. (a) Distribution of  $M_{\mu^+\mu^-}$  vs.  $M_{\text{miss}}$ , and the projection on  $M_{\text{miss}}$  from (b)-(d), the diagonal band  $|M_{\text{miss}} - M_{\mu^+\mu^-}| < 150 \text{ MeV}/c^2$  near the  $\Upsilon(1S)$ ,  $\Upsilon(2S)$  and  $\Upsilon(3S)$ ; and (e),(f), the horizontal band  $|M_{\mu^+\mu^-} - M[\Upsilon(1S)]| < 150 \text{ MeV}/c^2$  near the  $\Upsilon(2S)$  and  $\Upsilon(3S)$ .

TABLE II. The yield, mass and statistical significance from the fits to the  $M_{\text{miss}}$  distributions. The statistical significance is calculated from the difference in  $\chi^2$  between the best fit and the fit with the signal yield fixed to zero.

	Yield, $10^3$	Mass, $\text{MeV}/c^2$	Significance
$\Upsilon(1S)$	$105.2 \pm 5.8 \pm 3.0$	$9459.4 \pm 0.5 \pm 1.0$	$18.2\sigma$
$h_b(1P)$	$50.4 \pm 7.8^{+4.5}_{-9.1}$	$9898.3 \pm 1.1^{+1.0}_{-1.1}$	$6.2\sigma$
$3S \rightarrow 1S$	$56 \pm 19$	$9973.01$	$2.9\sigma$
$\Upsilon(2S)$	$143.5 \pm 8.7 \pm 6.8$	$10022.3 \pm 0.4 \pm 1.0$	$16.6\sigma$
$\Upsilon(1D)$	$22.0 \pm 7.8$	$10166.2 \pm 2.6$	$2.4\sigma$
$h_b(2P)$	$84.4 \pm 6.8^{+23.0}_{-10.0}$	$10259.8 \pm 0.6^{+1.4}_{-1.0}$	$12.4\sigma$
$2S \rightarrow 1S$	$151.7 \pm 9.7^{+9.0}_{-20.0}$	$10304.6 \pm 0.6 \pm 1.0$	$15.7\sigma$
$\Upsilon(3S)$	$45.6 \pm 5.2 \pm 5.1$	$10356.7 \pm 0.9 \pm 1.1$	$8.5\sigma$

The background polynomial order was increased by three, and the range of the fits performed were altered by up to  $100 \text{ MeV}/c^2$ . Different signal functions were used, including symmetric Gaussians and rCB functions with the width parameters left free. We altered our selection criteria: tightening the requirements on the proximity of track origin to the IP, increasing the minimum number of tracks to four, and imposing the  $\cos\theta_{\pi^+\pi^-} < 0.95$  requirement used in the  $\mu^+\mu^-\pi^+\pi^-$  study. In Table III a summary of our systematic studies is presented.

The values in the table represent the maximal change of parameters under the variations explored. We estimate an additional  $1 \text{ MeV}/c^2$  uncertainty in mass mea-

TABLE III. Absolute systematic uncertainties in the yields and masses from various sources.

	Polynomial order	Fit range	Signal shape	Selection requirements
$N[\Upsilon(1S)], 10^3$	$\pm 1.4$	$\pm 1.7$	$\pm 2.0$	—
$N[h_b(1P)], 10^3$	$\pm 2.4$	$\pm 3.6$	$^{+1.2}_{-8.0}$	—
$N[\Upsilon(2S)], 10^3$	$\pm 3.4$	$\pm 3.2$	$\pm 5.0$	—
$N[h_b(2P)], 10^3$	$\pm 2.2$	$\pm 2.6$	$^{+23.0}_{-9.0}$	—
$N[2 \rightarrow 1], 10^3$	$\pm 3.0$	$\pm 8.0$	$^{+0}_{-18}$	—
$N[\Upsilon(3S)], 10^3$	$\pm 1.0$	$\pm 3.0$	$\pm 4.0$	—
$M[\Upsilon(1S)], \text{MeV}/c^2$	$\pm 0.04$	$\pm 0.06$	$\pm 0.03$	$\pm 0.18$
$M[h_b(1P)], \text{MeV}/c^2$	$\pm 0.04$	$\pm 0.10$	$^{+0.04}_{-0.20}$	$^{+0.20}_{-0.30}$
$M[\Upsilon(2S)], \text{MeV}/c^2$	$\pm 0.02$	$\pm 0.08$	$\pm 0.06$	$\pm 0.03$
$M[h_b(2P)], \text{MeV}/c^2$	$\pm 0.10$	$\pm 0.20$	$^{+1.0}_{-0.0}$	$\pm 0.08$
$M[2 \rightarrow 1], \text{MeV}/c^2$	$\pm 0.20$	$\pm 0.10$	$\pm 0.06$	$\pm 0.10$
$M[\Upsilon(3S)], \text{MeV}/c^2$	$\pm 0.15$	$\pm 0.24$	$\pm 0.10$	$\pm 0.20$

surements based on the differences between the observed values of the fitted  $\Upsilon(nS)$  peak positions and their world averages. The total systematic uncertainties presented in Table II represent the sum in quadrature of all the contributions listed in Table III. The signal for the  $\Upsilon(1D)$  is marginal and therefore systematic uncertainties on its related measurements are not listed in the table. The significances of the  $h_b(1P)$  and  $h_b(2P)$  signals, with systematic uncertainties accounted for, are  $5.5\sigma$  and  $11.2\sigma$ ,

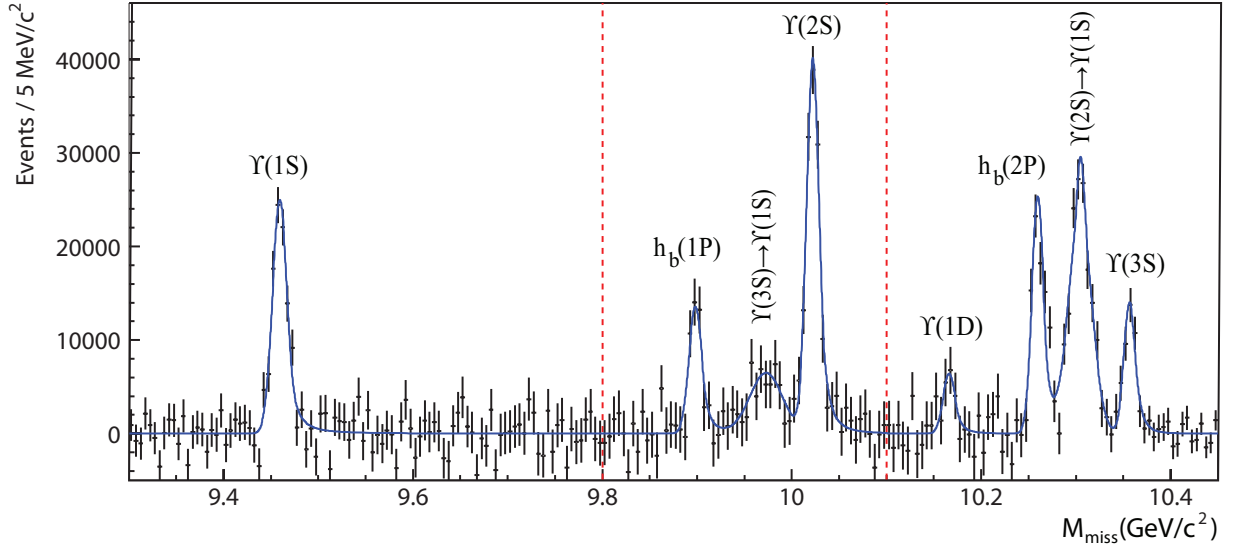


FIG. 3. The inclusive  $M_{\text{miss}}$  spectrum with the combinatoric background and  $K_S^0$  contribution subtracted (points with errors) and signal component of the fit function overlaid (smooth curve). The vertical lines indicate boundaries of the fit regions.

respectively.

The measured masses of  $h_b(1P)$  and  $h_b(2P)$  are  $M = (9898.3 \pm 1.1^{+1.0}_{-1.1}) \text{ MeV}/c^2$  and  $M = (10259.8 \pm 0.6^{+1.4}_{-1.0}) \text{ MeV}/c^2$ , respectively. Using the world average masses of the  $\chi_{bJ}(nP)$  states, we determine the hyperfine splittings to be  $\Delta M_{\text{HF}} = (+1.6 \pm 1.5) \text{ MeV}/c^2$  and  $(+0.5^{+1.6}_{-1.2}) \text{ MeV}/c^2$ , respectively, where statistical and systematic uncertainties are combined in quadrature.

We also measure the ratio of cross sections for  $e^+e^- \rightarrow \Upsilon(5S) \rightarrow h_b(nP)\pi^+\pi^-$  to that for  $e^+e^- \rightarrow \Upsilon(5S) \rightarrow \Upsilon(2S)\pi^+\pi^-$ . To determine the reconstruction efficiency we use the results of resonant structure studies reported in Ref. [12] that revealed the existence of two charged bottomonium-like states,  $Z_b(10610)$  and  $Z_b(10650)$ , through which the  $\pi^+\pi^-$  transitions we are studying primarily proceed. These studies indicate that the  $Z_b$  most likely have  $J^P = 1^+$ , and therefore in our simulations the  $\pi^+\pi^-$  transitions are generated accordingly. To estimate the systematic uncertainty in our reconstruction efficiencies, we use MC samples generated with all allowed quantum numbers with  $J \leq 2$ .

We find that the reconstruction efficiency for the  $\Upsilon(2S)$  is about 57%, and that those for the  $h_b(1P)$  and  $h_b(2P)$  relative to that for the  $\Upsilon(2S)$  are  $0.913^{+0.136}_{-0.010}$  and  $0.824^{+0.130}_{-0.013}$ , respectively. The efficiency of the  $R_2 < 0.3$  requirement is estimated from data by measuring signal yields with  $R_2 > 0.3$ . For  $\Upsilon(2S)$ ,  $h_b(1P)$  and  $h_b(2P)$  we find  $0.863 \pm 0.032$ ,  $0.723 \pm 0.068$  and  $0.796 \pm 0.043$ , respectively. From the yields and efficiencies described above, we determine the ratio of cross sections  $R \equiv \frac{\sigma(h_b(nP)\pi^+\pi^-)}{\sigma(\Upsilon(2S)\pi^+\pi^-)}$  to be  $R = 0.46 \pm 0.08^{+0.07}_{-0.12}$  for the  $h_b(1P)$  and  $R = 0.77 \pm 0.08^{+0.22}_{-0.17}$  for the  $h_b(2P)$ . Hence  $\Upsilon(5S) \rightarrow h_b(nP)\pi^+\pi^-$  and  $\Upsilon(5S) \rightarrow \Upsilon(2S)\pi^+\pi^-$  proceed at sim-

ilar rates, despite the fact that the production of  $h_b(nP)$  requires a spin-flip of a  $b$ -quark.

The rate of  $\Upsilon(5S) \rightarrow h_b(nP)\pi^+\pi^-$  is much larger than the upper limit for that of  $\Upsilon(3S) \rightarrow h_b(nP)\pi^+\pi^-$  obtained by the BaBarCollaboration [13]. This is consistent with the observation that the rates for  $\Upsilon(5S) \rightarrow \Upsilon(mS)\pi^+\pi^-$  with  $m = 1, 2, 3$  are much larger than those for  $\Upsilon(nS) \rightarrow \Upsilon(mS)\pi^+\pi^-$  for  $n = 2, 3, 4$  [5]. The only previous evidence for the  $h_b(1P)$  is a  $3.0\sigma$  excess in  $\Upsilon(3S) \rightarrow \pi^0 h_b(1P)$  at  $(9902 \pm 4) \text{ MeV}/c^2$  presented by BaBar [14].

We have also used  $711 \text{ fb}^{-1}$  of  $e^+e^-$  collisions at the  $\Upsilon(4S)$  resonance to search for  $\Upsilon(4S) \rightarrow h_b(1P)\pi^+\pi^-$  ( $h_b(2P)$  is kinematically forbidden). The overall efficiency, assuming the  $R_2$  efficiency at  $\Upsilon(4S)$  to be the same as that at  $\Upsilon(5S)$ , is  $0.94^{+0.11}_{-0.03}$  relative to that for  $\Upsilon(5S) \rightarrow h_b(1P)\pi^+\pi^-$ . From our observed yield of  $(35 \pm 21^{+24}_{-15}) \times 10^3$ , we therefore set an upper limit on the ratio of  $\sigma(e^+e^- \rightarrow h_b(1P)\pi^+\pi^-)$  at the  $\Upsilon(4S)$  to that at the  $\Upsilon(5S)$  of 0.27 at 90% C.L.

In summary, we have observed the  $P$ -wave spin-singlet bottomonium states  $h_b(1P)$  and  $h_b(2P)$  in the reaction  $e^+e^- \rightarrow \Upsilon(5S) \rightarrow h_b(nP)\pi^+\pi^-$ . The  $h_b(nP)$  masses correspond to hyperfine splittings that are consistent with zero. We also have observed that the cross sections for these processes and that for  $e^+e^- \rightarrow \Upsilon(5S) \rightarrow \Upsilon(2S)\pi^+\pi^-$  are of comparable magnitude, indicating the production of  $h_b(nP)$  at the  $\Upsilon(5S)$  resonance must occur via a process that avoids the expected suppression related to heavy quark spin-flip.

We thank the KEKB group for excellent operation of the accelerator, the KEK cryogenics group for efficient solenoid operations, and the KEK computer group

and the NII for valuable computing and SINET4 network support. We acknowledge support from MEXT, JSPS and Nagoya's TLPRC (Japan); ARC and DIISR (Australia); NSFC (China); MSMT (Czechia); DST (India); MEST, NRF, NSDC of KISTI, and WCU (Korea); MNiSW (Poland); MES and RFAAE (Russia); ARRS (Slovenia); SNSF (Switzerland); NSC and MOE (Taiwan); and DOE and NSF (USA).

- 
- [1] N. Brambilla *et al.*, Eur. Phys. J. C **71**, 1534 (2011).
  - [2] S. Godfrey and J. L. Rosner, Phys. Rev. D **66**, 014012 (2002).
  - [3] S. Dobbs *et al.* (CLEO Collaboration), Phys. Rev. Lett. **101**, 182003 (2008); M. Albikim *et al.* (BES Collaboration), Phys. Rev. Lett. **104**, 132002 (2010).
  - [4] T. K. Pedlar *et al.* (CLEO Collaboration), Phys. Rev. Lett. **107**, 041803 (2011).
  - [5] K.-F. Chen *et al.* (Belle Collaboration), Phys. Rev. Lett. **100**, 112001 (2008).
  - [6] A. Abashian *et al.* (Belle Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **479**, 117 (2002).
  - [7] S. Kurokawa and E. Kikutani, Nucl. Instrum. Methods Phys. Res. Sect., A **499**, 1 (2003), and other papers included in this Volume.
  - [8] K. Abe *et al.* (Belle Collaboration), Phys. Rev. D **64**, 072001 (2001).
  - [9] G.C. Fox and S. Wolfram, Phys. Rev. Lett. **41**, 1581 (1978).
  - [10] J. E. Gaiser, Ph. D. thesis, SLAC-R-255 (1982) (unpublished); T. Skwarnicki, Ph.D. thesis, DESY F31-86-02 (1986) (unpublished).
  - [11] K. Nakamura *et al.* (Particle Data Group), J. Phys. G **37**, 075021 (2010).
  - [12] I. Adachi *et al.* (Belle Collaboration), arXiv:1105.4583.
  - [13] J. P. Lees *et al.* (BaBar Collaboration), arXiv:1105.4234.
  - [14] J. P. Lees *et al.* (BaBar Collaboration), arXiv:1102.4565.